Tillage and perennial grass effects on ponded infiltration for seven semi-arid loess soils

S.B. Wuest, J.D. Williams, and H.T. Gollany

ABSTRACT: To test the benefits of no-till, we measured steady-state ponded water infiltration on a Pacific Northwest geo-climo sequence of seven semi-arid soils where no-till, conventional till, and perennial grass fields were in close proximity. Average infiltration was 30 percent greater under no-till and grass compared to conventional tillage, although variability among sites and years was high. This indicates that these practices can reduce the potential for runoff and erosion when measured over many sites, but might not at a particular site. Infiltration correlated positively with sand content (r = 0.75), negatively with silt (r = -0.78), but was not correlated with water stable aggregates because texture had a dominant effect. The number of years since tillage was positively correlated with infiltration, particulate organic matter, permanganate oxidizable C (active C) and organic C (r = 0.58, 0.70, 0.50, and 0.57 respectively). Among soil properties, organic C was positively correlated with active C, particulate organic matter, water stable aggregates, and silt (r = 0.92, 0.63, 0.38, and 0.41, respectively). Despite high variability and the need for numerous subsamples, measurement of infiltration was an effective test for documenting benefits of no-till. Additional research with correlated indicators appears warranted, but researchers should be cautious in assuming their relationship to infiltration.

Keywords: Aggregates, infiltration, no-tillage, organic carbon, perennial grass

Soil erosion is one of the most pernicious consequences of human activity, continuing to degrade the earth's productivity even in nations with advanced agricultural technology. Where erosion-resistant practices have been proposed or developed, encouraging adoption or adaptation by local farmers is still a major challenge. Farmers question whether the proposed practices will be effective when implemented on a farm scale. The resistance may be justified because the original innovation has often been tested on a limited range of soil types and promoted by farmers or researchers philosophically dedicated to certain principles or goals without fully acknowledging the risks or changes required.

In the Pacific Northwest, a majority of farmers leave more stubble on the soil surface than was common two decades ago, but less than 10 to 20 percent consistently practice no-till (Smiley et al., 2005). In dryland production regions, perennial grass is mostly limited to federal Conservation Reserve Program acres and a limited amount of grassed waterways. Our intention was to examine how well the innovator's concepts and descriptions of no-till production on semi-arid loess soils translated to effectiveness when adopted by average farm managers on different soil types.

For example, a practice like no-till might be very effective in increasing water infiltration on soils with the ability to form relatively strong aggregates (Burch et al., 1986), but small differences in soil texture or crop residue production can have large effects on infiltration (Shaver et al., 2002). The effect of no-till on infiltration has also been demonstrated to be time-dependent and variable from year to year (Wienhold and Tanaka, 2000). In climates where raindrop impact or freezing and thawing have a substantial influence on surface crusts, the amount of surface residue (Shaver et al., 2002; Radcliffe et al., 1988), biopore preservation (McGarry et al., 2000) or accumulation of soil organic carbon on the surface (Franzluebbers, 2002; Burch et al., 1986) have been credited with improving water infiltration.

Conventional tillage inverts or at least stirs the soil, totally or partially burying crop residues. No-till allows crop residue to accumulate on the surface. The effect of surface soil characteristics on infiltration depends on the interaction between soil, surface residues, time, and weather in a particular year. Even a single tillage operation can interrupt the gradual change brought about by no-till systems and produce long-term changes in infiltration (Kettler et al., 2000). Therefore farmers following the same basic guidelines might get different results even on the same soil and in the same climate.

This paper summarizes our initial efforts to quantify the effectiveness of no-till winter wheat (*Triticum aestivum* L.) production for protecting fields from soil erosion by increasing infiltration capacity, in comparison to conventionally tilled wheat production practices and perennial grass stands. Our goal was to determine if a relatively simple but direct measurement of steady-state ponded water infiltration rates could distinguish among three well-recognized soil management practices implemented by different farmers on seven soil types in a geo-climo sequence across north-central Oregon.

Materials and Methods

Fields were chosen from the major soil series that represent winter wheat/fallow farming in Umatilla County, Oregon. The soil series and selected soil properties are shown in Table 1. One of the sites (Walla Walla soil) is located on an agricultural research station with long-term experimental plots used to represent the chosen practices. The other six sites are farmers' fields with no-till and conventional winter wheat/summer fallow man-

Stewart B. Wuest is a soil scientist for the U.S. Department of Agriculture Agricultural Research Service (USDA-ARS) at the Columbia Plateau Conservation Research Center in Pendleton, Oregon. **John D. Williams** is a hydrologist for the USDA-ARS at the Columbia Plateau Conservation Research Center in Pendleton, Oregon. **Hero T. Gollany** is a soil scientist for the USDA-ARS at the Columbia Plateau Conservation Research Center in Pendleton, Oregon.

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Table 1. Soil series names and descriptions at the seven sites plus selected measured parameters. Sand, silt, clay, particulate organic matter (POM), percolation and active C were measured on 0 to 10 cm samples.

Soil series	Practice	Years since tillage		sand	silt	clay	POM	percolation	ActiveC	Earthworm	Water stable aggregate	
											0-2.5 cm	2.5-10 cm
		2002	2004	—— kg kg^{-1} ——			g kg^{-1}	ml min^{-1}	mg kg^{-1}	m^{-2}	—— kg kg^{-1} ——	
Thatuna silt loam	Conventional	0	2	0.14	0.71	0.14	8.14	0.14	1222	8	0.969	0.962
fine-silty, mixed, superactive,	No-till	4	6	0.19	0.68	0.12	9.86	0.16	1252	445	0.770	0.791
mesic Oxyaquic Argixeroll	Grass	16	18	0.17	0.69	0.14	7.46	0.18	1138	35.5	0.944	0.938
Morrow silt loam	Conventional	0	0	0.16	0.73	0.11	4.70	0.13	733	0	0.893	0.945
fine-silty, mixed, superactive,	No-till	4	6	0.19	0.71	0.09	9.47	0.15	927	0	0.906	0.931
mesic Calcic Argixeroll	Grass	2	4	0.16	0.75	0.09	3.89	0.09	649	0	0.890	0.943
Walla Walla silt loam	Conventional	0	0	0.22	0.65	0.13	4.58	0.08	633	72	0.914	0.815
coarse-silty, mixed, superactive,	No-till	20	22	0.21	0.69	0.10	8.70	0.16	1081	92	0.877	0.807
mesic Typic Haploxeroll	Grass	71	73	0.21	0.68	0.10	14.88	0.21	1217	263	0.962	0.962
McKay silt loam	Conventional	0	0	0.20	0.70	0.09	4.70	0.05	624	12	0.817	0.792
fine-silty, mixed, superactive,	No-till	4	6	0.23	0.69	0.08	8.11	0.11	773	29	0.924	0.846
mesic Calcic Argixeroll	Grass	4	6	0.20	0.69	0.10	8.38	0.17	844	76.5	0.893	0.748
Athena silt loam	Conventional	0	1	0.24	0.66	0.09	7.26	0.10	817	41.5	0.960	0.960
fine-silty, mixed, superactive,	No-till	5	7	0.26	0.63	0.10	9.91	0.16	1029	4	0.915	0.944
mesic Pachic Haploxeroll	Grass	35	37	0.34	0.56	0.09	9.61	0.24	916	62.5	0.967	0.960
Ritzville silt loam	Conventional	0	0	0.41	0.52	0.07	6.20	0.14	609	0	0.914	0.952
coarse-silty, mixed, superactive,	No-till	2	4	0.35	0.58	0.07	6.37	0.23	819	8	0.886	0.897
mesic Calcidic Haploxeroll	Grass	1	3	0.42	0.52	0.05	6.05	0.12	551	0	0.755	0.927
Shano very fine sandy loam	Conventional	0	0	0.63	0.32	0.04	10.78	1.34	805	0	0.882	0.865
coarse-silty, mixed, superactive,	No-till	5	7	0.58	0.37	0.04	8.09	0.37	636	0	0.731	0.744
mesic Xeric Haplocambid	Grass	15	17	0.86	0.10	0.03	9.20	0.35	736	0	0.645	0.675

agement systems and perennial grass planted in close proximity. Close proximity does not ensure that the three management practices were performed on soils with identical characteristics, because field boundaries and especially land taken out of production for perennial grass plantings are often determined by productivity or difficulty in farming. Care was taken to choose comparable sites and avoid field edges or corners. The sites were level to gently sloping, representative of a majority of the field. The three practices at each site were generally much less than 1 km (0.6 mi) apart, although at one site they were about 3 km (1.8 mi) apart. The arable soils in this county are part of a much larger loess deposit on the Columbia Plateau, and soil texture at each site is relatively uniform over distances of kilometers. The same prevailing wind that determined gradations in soil texture also determines annual precipitation (ranging from 200 to 550 mm; 8 to 22 in), resulting in coarser soils at the warmer, drier, lower elevations, and finer soils at cooler, moister, higher elevations. As a consequence, organic matter accumulation and crop productivity are confounded with soil texture, because plant growth is water limited in this semi-arid environment. It should also be noted that different farmers implemented the soil management practices on each of the seven soil types, so management methods are confounded with soil type and climate. The most exceptional management practice was the addition of onion (*Allium cepa*) processing-plant waste as a soil amendment on the Shano soil, conventional practice. This waste was disked into the surface 10 cm (4 in).

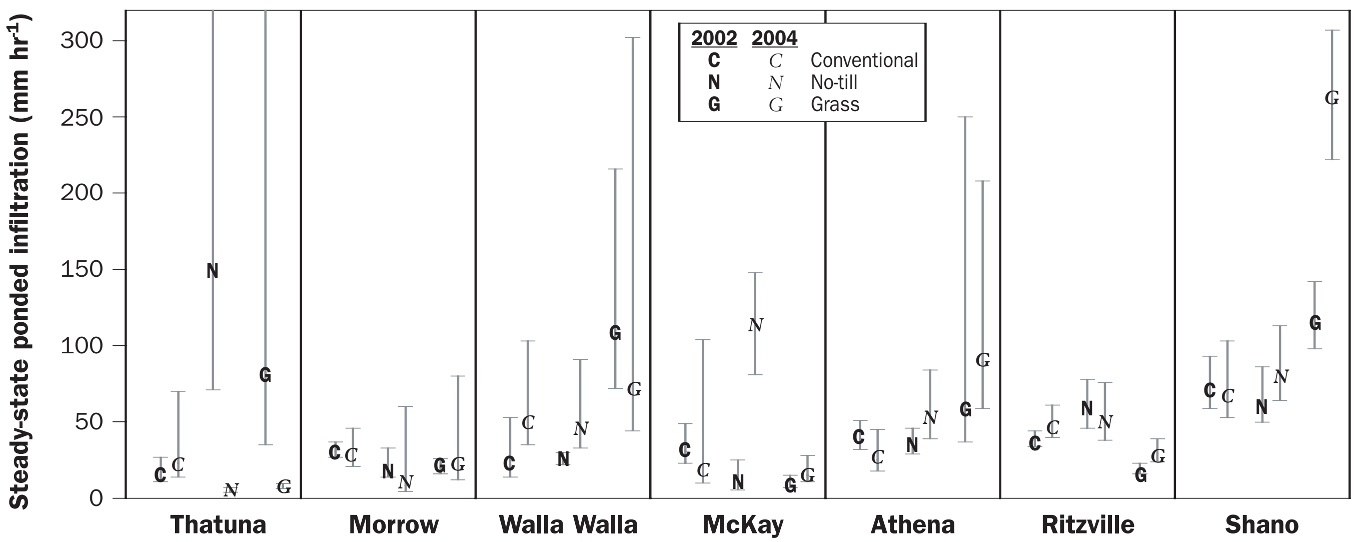
In general, conventional tillage involves incorporation of wheat residues after harvest with a plow, disk, or chisel, followed by cultivation and rodweeding throughout the summer fallow period. No-till relies on herbicides to control weeds during summer fallow, and there is often no soil disturbance before the seeding of winter wheat. Six ponded infiltration measurements were made in each treatment at each site in 2002 and again in 2004. The measurements were made during ripening or soon after harvest of winter wheat (with one exception on the Thatuna soil, no-till practice, which was fallow in 2002). Single-ring infiltration measurements (Bertrand, 1965) were made by driving 20-cm (8-in) diameter sharpened metal cylinders 25 cm (10 in) deep into the soil. Part of a crop row was always included inside the sample area. The inside circumference was tamped to seal any gaps between the cylinder and the soil. Water was then maintained at a constant depth of 2 to 3 cm (0.75 to 1.2 in) with float valves for two hours. Readings from calibrated reservoirs supplied periodic estimates of water infiltration rate. Two hours was sufficient to achieve near steady-state infiltration, which was usually approached within 30 to 60 minutes.

Soil samples were taken from the surface to 2.5-cm (1-in) and 2.5- to 10-cm (1- to 4-in) depths in 2002. The samples were analyzed for total C and N by combustion analysis. There were no significant surface carbonates in the soils so combustion and loss-on-ignition analyses accurately measure organic carbon forms. Percent of 1 to 2 mm (0.04 to 0.08 in) diameter aggregates that were water-stable were determined by a method modified from Kemper and Rosenau (1986) where aggregates are vapor wetted before wet sieving, and sand is subtracted from stable aggregate weight (Gollany et al., 1991).

In 2004, a composite of three cores were taken from 0 to 10 cm (0 to 4 in). The samples were analyzed for organic C, texture and particulate organic matter, easily oxidizable C, and percolation. Organic C was measured using a Primacs SC total organic carbon

Figure 1

Steady-state ponded infiltration measured in 2002 and 2004 under conventional and no-till winter wheat/fallow management and perennial grass plantings. The seven soil types are arranged in order of increasing sand (>53 µm) content. Symbols C, N, and G mark the means (n=6). Confidence intervals at 90 percent (α = 0.05 for both upper and lower confidence limits) calculated using the method of Land (Parkin and Robinson, 1992) are shown for each mean.



combustion analyzer (Skalar Analytical B.V., The Netherlands). Soil texture and particulate organic matter were measured using the sieve and loss-on-ignition method of Cambardella et al. (2001), except we used only 15 g (0.03 lb) of soil, and therefore did not subsample when determining silt and clay. Readily oxidizable C (referred to as active C) was measured using the method of Weil et al. (2003), in which reduction of 0.02M $KMnO_4$ by soil organic matter is measured using a spectrophotometer.

The percolation test (Auerswald, 1995) measures the rate of percolation through small soil columns under a constant head. Tubes 16-mm (0.62 in) inner diameter with screens attached to the bottom were filled with a 2-mm (0.8-in) layer of coarse sand, followed by 10 g (0.02 lb) soil. A 2-mm (0.8-in) layer of sand plus a loose plug of gauze on top of the soil protected the surface of the soil. The filled tube was dropped 2 cm (0.79 in) onto a hard surface 10 times to pack it to a more uniform density. Deionized water poured into the tube above the soil maintained a 20-cm (8 in) head. The rate of percolated water leaving the bottom of the tubes was measured for five minutes after 20 minutes had passed. Data presented is the average of four subsamples.

Earthworm populations were estimated from a composite of four 20-cm (8 in) diameter cores from 0- to 25-cm (0- to 10-in) depth taken both years in all treatments. Earthworm populations are low in this region, and it is difficult to sample enough soil to estimate population levels if only clitellete specimens are counted. Therefore, the soil was washed through a 1.4 mm sieve (0.05 in) and any worm, from cocoon to mature developmental stage, was counted.

Ponded infiltration measurements produce data with a log normal distribution (Sission and Wierenga, 1981; Wuest, 2005). In order to compare mean infiltration among treatments we computed 90 percent confidence intervals for each mean using the method of Land (Parkin and Robinson, 1992). Means with confidence intervals that do not overlap were considered significantly different. Pearson correlation coefficients were also calculated among measured factors, and tested for significance by $p > |r|$ (SAS 1998).

Results and Discussion

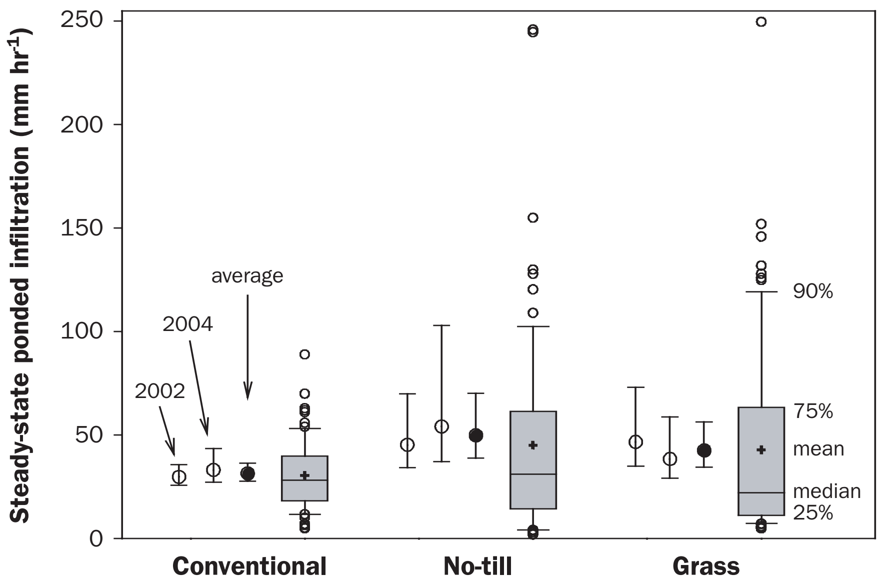
Steady-state ponded infiltration varied as much from the first year to the second as from practice to practice and soil-to-soil (Figure 1). Variance between individual cylinder measurements (indicated by confidence intervals) tends to increase with the mean as is characteristic of log normal data. The soils with less sand content have much lower minimum infiltration rates, but can have very high rates under certain conditions. An example is the 2002 measurement of the Thatuna no-till and grass.

The Shano soil was the coarsest of the seven soils, and texture variation the greatest (Table 1). The infiltration estimate for grass in 2004 was very high, although it did not differ from the 2002 estimate in a disproportionate manner when compared to the variation measured for other soils (Figure 1). In order to prevent the very sandy Shano-grass treatment from having an extreme influence on the comparison of soil management treatments, the Shano soil is excluded from selected analyses.

Infiltration averaged over years and soils (excluding Shano) differed significantly among the three practices (Figure 2). Average steady ponded infiltration rate was significantly greater under grass (43 mm hr^{-1}; 1.69 in hr^{-1}) and no-till (45 mm hr^{-1}; 1.77 in hr^{-1}) when compared to conventional tillage (31 mm hr^{-1}; 1.22 in hr^{-1}). When considered separately, results from the individual years were too variable to draw conclusions.

Measurements of percolation through small columns of disturbed soil gave the same results as steady-state ponded infiltration of *in situ*, intact cores if the Shano soil was removed from the analysis. Mixed model analysis-of-variance showed grass and no-till both having significantly greater percolation than conventional wheat production ($p > |t|$, <0.0002). The Shano conventional practice, where onion waste had been incor-

Figure 2
Means for soil management treatments (excluding Shano soil) by year (n=36), and averaged over both years of measurement (n=72) with box plots. Confidence intervals at 90 percent ($\alpha = 0.05$ for both upper and lower confidence limits) calculated using the method of Land (Parkin and Robinson, 1992) are shown for each mean.



porated to 10-cm (4-in) depth, demonstrated extremely high percolation through surface soil (0- to 10-cm, 0- to 4-in) (Table 1), although ponded infiltration measurements did not appear to be affected (Figure 1). Particulate organic matter, active C, and water stable aggregates are also higher than might be normally expected for this practice and soil.

Although not a primary objective of the research, soil analyses were explored for potential correlation to infiltration. Some soil measurements commonly thought to be important for good soil structure and water infiltration are shown in Figure 3. Water stable aggregates from 0- to 2.5-cm (0- to 1-in) soil depth are shown in preference to 2.5- to 10-cm (1- to 4-in) depth because they demonstrated consistently better correlations and p values. Silt content was representative of soil texture, since it was very closely related to the small amount of clay found in these soils and inversely related ($r = -0.99$, $p > |r|$ 0.0001) to sand content. Silt content was negatively correlated ($r = -0.49$) with infiltration rate. Water stable aggregates were positively correlated with silt ($r = 0.37$) and not correlated with infiltration rate. Particulate organic matter ($r = 0.62$) and years since tillage ($r = 0.58$) have significant positive correlations with infiltration. Organic C is well correlated with active C, and somewhat correlated to silt, particulate organic matter, and water stable aggregates.

The 2002 infiltration estimate on the Thatuna soil, no-till practice (Figure 1) may be high because it was in fallow instead of winter wheat at the time of measurement. Untilled stubble generally has greater infiltration than immature winter wheat (Wuest, 2005). The grass at that site also exhibited much greater infiltration in 2002 than in 2004, indicating that year-to-year variation may have played a role as well.

The best test of protection from erosion would be a direct measure of runoff and erosion over many years, using small watershed or runoff plot monitoring. Such investigations are very expensive. Ponded infiltration is not a direct measure of the capacity of a soil to resist erosion, but is a relatively quick point measurement of water intake capacity and also how rapidly the surface soil drains when saturated. De-saturation is important in the Pacific Northwest because thawing snow or rainfall on frozen soil is a major cause of soil erosion (Zuzel et al., 1982), and air-filled porosity determines whether frozen soil contains any open passages for water infiltration. Ponded infiltration using deeply-driven cylinders measures the interaction of both surface and subsurface soil factors such as soil crusts, slaking, compaction, and pore connectivity.

Our ponded infiltration tests did indicate that grass and no-till, on average, have greater infiltration capacity (Figure 2). The number of years no-till and grass have been practiced on a field appears to be very important. For example, despite an excellent stand of grass on the Morrow and McKay soils, after four to six years they still have lower infiltration rates than the nearby conventional fields (Figure 1). During an erosive event the grass field would undoubtedly lose much less soil, but it would likely yield large amounts of runoff. It apparently can take many years after seeding into tilled cropland for a grass stand to produce high infiltration rates.

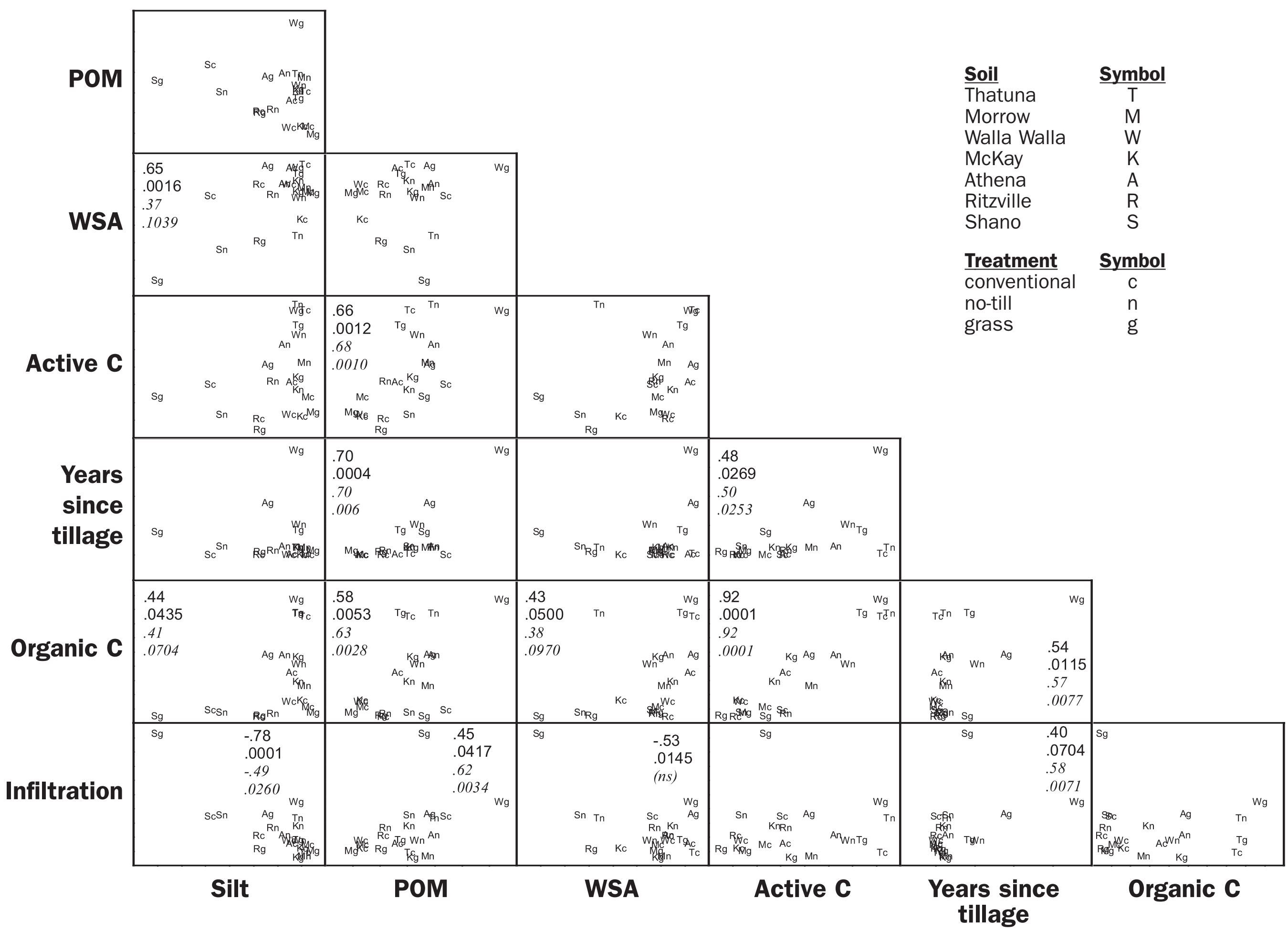
The number of years since the last tillage was correlated with particulate organic matter and active C, and also earthworm populations ($r = 0.42$, $p > |r|$ 0.0551). Tillage mixes surface residues throughout the plow layer, decreasing its concentration in the surface soil and enhancing its rate of oxidation. Concentrated organic matter provides substrates for microorganisms, which enhances soil aggregation. Untilled soil provides a better environment for earthworms, probably due to a more concentrated food source and reduced soil disruption. The earthworms identified in agricultural fields in this region are *Apporectodea trapezoides* (Duges). This species is endogeic, living and feeding mostly at a shallow depth under the surface and not producing many deep, vertical pores connected to the surface. Our observations, based on examination of hundreds of infiltration cylinders exhumed and examined for flow patterns, including the present study, is that earthworm pores are not related to ponded water infiltration rates in this region.

Water stable aggregates are generally helpful in improving water infiltration, especially through the surface of the soil, but on this catena of soils their effect is overwhelmed by the effect of soil texture. Apparently, when the ponded infiltration rate of the entire Ap horizon was measured, the effect of surface aggregation was less important than the overall texture of the soil (Figure 3). Since organic matter accumulation was associated with the relatively cool, moist, high elevation sites that also have fine soil textures, water stable aggregates at the surface turned out to be not correlated with water infiltration (when the outlier Shano- grass is excluded). Buman et al. (2004) reported similar results in a study conducted in the Midwest. They found that surface soil characteristics and infiltration were not always sensitive to soil management treatments carried out for a five-year period.

For practical reasons, the infiltration meas-

Figure 3

Scatter plot matrix of selected soil measurements. Pearson correlation coefficients and p > |r| are shown for relationships with p < 0.1 for all points, then again below in italics excluding the Shano-grass treatment. POM = particulate organic matter, and WSA = water stable aggregates.



urements were made during the summer. The Pacific Northwest has a Mediterranean climate, with about 70 percent of precipitation occurring as rain during the winter. Winter is when most erosion occurs, and it is possible that different and more pertinent results would have been obtained if the measurements had been performed during the winter or very early spring. Then the capacity of the soil to resist crusting and maintain structure during freeze-thaw cycles would be better tested. It is possible that growth of the wheat crown and root system allowed the conventional tillage practice to exhibit greater infiltration during the summer than would occur while the wheat was small (Wuest, 2005). It is evident from this dataset, however, that evaluation of soil management practices requires careful consideration of soil textural variation, year-to-year measurement variation, and especially variations in the length of time a soil has been managed in a prescribed way. Even after four to six years without tillage, infiltration in a particular field may not improve, and indeed may be poorer compared to conventional tillage, although susceptibility to soil erosion would likely be diminished.

Summary and Conclusion

Ponded water infiltration rates measured during summer indicated better infiltration for no-till wheat and perennial grass plantings compared to conventional wheat production when averaged over seven soils and two years. At any single location or in any single year, the results varied depending on previous site history, such as how long the practices have been in place, how the practices were implemented, and the ability of that soil to accumulate surface organic C. Soil characteristics like water stable aggregates or active C in the soil surface may be misleading if used as an indirect predictor of soil performance, because they might not reflect infiltration capacity of the soil to a sufficient depth. They may, however, prove useful for comparisons of management practices on a particular soil once their relationship to a particular soil function is determined.

Endnote

Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

References Cited

Auerswald, K., 1995. Percolation stability of aggregates from arable topsoils. Soil Science 159:142-148.

Buman, R.A., B.A. Alesii, J.L. Hatfield, and D.L. Karlen. 2004. Profit, yield, and soil quality effects of tillage systems in corn-soybean rotations. Journal Soil Water Conservation 59(6):260-270.

Bertrand, A.R. 1965. Rate of water intake in the field. Pp. 197-209. *In:* Methods of soil analysis. Part 1. C.A. Black (ed.) Agronomy Monogram No. 9. American Society of America and Soil Science Society of America, Madison Wisconsin.

Burch, G.J., Mason, I.B., Fischer, R.A., and I.D. Moore. 1986. Tillage effects on soils: Physical and hydraulic responses to direct drilling at Lockhart, N.S.W. Australian Journal Soil Research 24:377-391.

Cambardella, C.A., A.M. Gajda, J.W. Doran, B.J. Wienhold, and T.A. Kettler. 2001. Estimation of particulate and total organic matter by weight loss-on-ignition. Pp. 349-359. *In:* Assessment methods for soil carbon. R. Lal, J.M. Kimble, R.F. Follett, and B.A. Stewart (ed.) CRC Press, Boca Raton, Florida.

Franzluebbers, A.J. 2002. Water infiltration and soil structure related to organic matter and its stratification with depth. Soil Tillage Research 66:197-205.

Gollany, H.T., T.E. Schumacher, P.D. Evenson, M.J. Lindstrom, and G.D. Lemme. 1991. Aggregate stability of an eroded and desurfaced Typic Argiustoll. Soil Science Society of America Journal 55:811-816.

Kettler, T.A., D.J. Lyon, J.W. Doran, W.L. Powers, and W.W. Stroup. 2000. Soil quality assessment after weed-control tillage in a no-till wheat-fallow cropping system. Soil Science Society of America Journal 64:339-346.

Kemper, W.D. and R.C. Rosenau. 1986. Aggregate stability and size distribution. Pp. 425-441. *In:* Methods of soil analysis. Part 1. 2nd edition. A. Klute (ed.) Agronomy Monogram No. 9. American Society of America and Soil Science Society of America, Madison Wisconsin.

McGarry, D., B.J. Bridge, and B.J. Radford. 2000. Contrasting soil physical properties after zero and traditional tillage of an alluvial soil in the semi-arid subtropics. Soil Tillage Research 53:105-115.

Parkin, T.B. and J.A. Robinson. 1992. Analysis of log normal data. Advances in Soil Science 20:193-235.

Radcliffe, D.E., E.W. Tollner, W.L. Hargrove, R.L. Clark, and M.H. Golabi. 1988. Effect of tillage practices on infiltration and soil strength of a Typic Hapludult soil after ten years. Soil Science Society of America Journal 52:798-804.

SAS Institute Inc., 1998. SAS Proprietary Software, Version 7. SAS Institute, Cary, North Carolina.

Shaver, T.M., G.A. Peterson, L.R. Ahuja, D.G. Westfall, L.A. Sherrod, and G. Dunn. 2002. Surface soil physical properties after twelve years of dryland no-till management. Soil Science Society of America Journal 66:1296-1303.

Sisson, J.B. and P.J. Wierenga. 1981. Spatial variability of steady-state infiltration rates as a stochastic process. Soil Science Society of America Journal 45:699-704.

Smiley, R.W., M.C. Siemens, T.M. Gohlke, and J.K. Poore. 2005. Small grain acreage and management trends for eastern Oregon and Washington. Agricultural Experiment Station, Oregon State University, Special Report No. 1061:30-50.

Weil, R.R., K.R. Islam, M.A. Stine, J.B. Gruver, S.E. Samson-Liebig. 2003. Estimating active carbon for soil quality assessment: A simplified method for laboratory and field use. American Journal of Alternative Agriculture 18:3-17.

Wienhold, B.J. and D. L. Tanaka. 2000. Haying, tillage, and nitrogen fertilization influences on infiltration rates at a conservation reserve program site. Soil Science Society of America Journal 64:379-381.

Wuest, S.B. 2005. Bias in ponded infiltration estimates due to sample volume and shape. Vadose Zone Journal 4:1183-1190.

Zuzel, J.F., R.R. Allmaras, and R. Greenwalt. 1982. Runoff and soil erosion on frozen soils in northeastern Oregon. Journal Soil and Water Conservation 57(6):351-354.